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SI Handbook for the Lawrence Livermore National Laboratory

Committee on Metric Transition
Lawrence Livermore National Laboratory

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SI HANDBOOK FOR THE LAWRENCE LIVERMORE NATIONAL LABORATORY

1.0 Background

1.1 Purpose of the SI Handbook

This Handbook is a guide to the use of the International System of Units[1] (SI) at the Lawrence Livermore National Laboratory. It describes the reasons for the United States converting to the metric system, legislation related to metric conversion, why the Laboratory is converting to the metric system, how international standards are established, the structure of SI, rules for using SI units and symbols, allowable non-SI units, and other important information about SI units and international standards. This handbook also demonstrates techniques for converting between inch-pound and metric units, and it contains tables of conversion factors.

In this handbook the terms *International System of Units* and *metric system* are used interchangeably.

1.2 Why the United States Needs to Convert to the Metric System

The primary motivation for the United States converting to the metric system is economic. Every developed country in the world — except the United States — is metric. NAFTA and the recently ratified GATT agreement involve lower tariffs which will increase trade among member nations. Not using metric units hurts our ability to compete in world markets, which is essential to our economic health and ultimately to our national security.

Because many markets are now global, there is more interdependence among nations today than even in the recent past. Also, technology is making our world smaller. Technological change and global dependence are powerful forces behind the establishment of worldwide standards in many different areas. In measurement, there is only one international standard: the System of International Units.

1.3 Metric Legislation

There are three important pieces of recent legislation that directly relate to metric conversion:

- Metric Study Act (1968)
- Metric Conversion Act (1975)
- Public Law 100-418 (1988)

In 1965, the United Kingdom decided to convert to the metric system which was a necessary condition for Britain to join the European Common Market (now called the European Union). Once this decision was made, it was obvious that soon the United States would stand alone as the only industrialized nation in the world that did not use metric units. Congress addressed this dilemma by passing the *Metric Study Act* which directed the

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[1]The formal name is French, Le Système Internationale d'Unité, hence the abbreviation SI.

Secretary of Commerce to study the impact of the U.S. conversion to using metric units. The conclusion reached in the study is revealed in the title of its report: **A METRIC AMERICA: A Decision Whose Time Has Come**.

In response to this report, Congress passed the *Metric Conversion Act* in 1975. This law strongly encouraged metric conversion, but it did not make conversion mandatory. Also, it did not give details on how the conversion was to take place.

Thirteen years later Congress amended the Metric Conversion Act with *Public Law 100-418.* This law states in part:

It is therefore the declared policy of the United States—

> *(1) to designate the metric system of measurement as the preferred system of weights and measures for United States trade and commerce.*
>
> (2) to require that each Federal agency, by a date certain and to the extent economically feasible by the end of the fiscal year 1992, use the metric system of measurement in its procurements, grants, and other business-related activities, except to the extent that such use is impractical or is likely to cause significant inefficiencies or loss of markets to United States firms, such as when foreign competitors are producing competing products in non-metric units.
>
> (3) to seek out ways to increase understanding of the metric system of measurement through educational information and guidance and in Government publications; and
>
> (4) to permit the continued use of traditional systems of weights and measures in non-business activities.

Thus, Federal agencies are now required by law to use metric units.

The Executive Branch also joined the push to metric conversion. On July 25, 1991, President George Bush signed Executive Order (EO) 12770 entitled *Metric Usage in Federal Government Programs*. EO 12770 provided Presidential authority and direction for the use of the metric system by Federal departments and agencies in their programs. This order also gave the Secretary of Commerce the authority to issue regulations to carry out government metrication as well as the responsibility to report annually to the President on progress toward metric transition.

Although Federal agencies did not meet the October, 1992 deadline for metric conversion, most agencies have developed metric transition plans and are in the process of transitioning to the use of metric units. The next few years should see an acceleration of metric conversion efforts, although full conversion may not be accomplished until the next century.

1.4 Metric Conversion at Lawrence Livermore National Laboratory

The Department of Energy (DOE) has developed and is in the process of implementing its metric transition plan. The Laboratory has been active in assisting the DOE in its metric transition efforts. Metric conversion is now a part of the contract between the Department of Energy and the University of California. Therefore, the Laboratory is both mandated by law and bound by contract to convert to the metric system.

To facilitate the Laboratory's conversion to the metric system, a committee was formed to develop a metric transition plan for the Laboratory. This document is part of that plan.

1.5 Origin of the Metric System

The metric system originated in France about 200 years ago. In 1790 the National Assembly of France authorized the French Academy of Sciences to develop a new system of measurement. The system was to satisfy two constraints:

- It was to be based on a fact or facts of nature.
- It was to be capable of being used by the entire world.

In 1799 the National Assembly formally adopted the metric system, although the use of the metric system was not made mandatory for French citizens.

The metric system had units for length (meter), mass (gram), volume (liter), and area (are). The original definition of each of these units is given below:

meter: one ten-millionth of the great circle distance form the north pole to the equator on the meridian through Paris.

gram: the mass of a cube of pure water one hundredth of a meter on each edge.

liter: the volume of a cube one tenth of a meter on each edge.

are (pronounced *air*) is the area of a square, ten meters on each side.

Larger and smaller units were formed by multiplying or dividing the size of the stem units by powers of 10 (10^1 = 10, 10^2= 100, 10^3 = 1000, etc.). Names for these units were formed by adding a prefix to the name of the stem unit. The original prefixes were as follows:

deci	0.1	deka	10
centi	0.01	hecto	100
milli	0.001	kilo	1000

The original prefixes for submultiples (smaller units) came from the Romans. Prefixes for multiples (larger units) came from the Greeks.

2.0 Authority for Determining Standards

2.1 The Constitution of the United States

The Constitution of the United States grants Congress authority to determine uniform standards of weights and measures.

Article 1, Section 8:

Congress shall have Power ....

> To coin Money, regulate the Value thereof, and of foreign Coin, and fix the Standard of Weights and Measures.

Scientific and technical responsibility for developing standards of many kinds has been assigned to the National Institute of Standards and Technology (NIST), which is part of the Department of Commerce. (NIST was formerly known as the National Bureau of Standards.)

To help government agencies and private industry convert to the metric system, the Federal government established the **Metric Program Office**. This office is a part of NIST and currently resides at NIST headquarters in Gaithersburg, Maryland.

2.2 International Standards

As international trade increased in the 1800s, it became obvious that international standards of measurement must be established. In 1875, after a 5-year conference on the subject, **The Treaty of the Meter** was signed by seventeen nations, including the United States. (By 1991, forty-six nations had signed the treaty.) This treaty established an organizational structure for determining international standards. The organizational structure consists of three levels:

Conférence Générale des Poids et Mesures (CGPM)

Comité International des Poids et Mesures (CIPM)

Bureau International des Poids et Mesures (BIPM)

CGPM consists of delegates from all of the Member Nations (nations who have signed the Treaty of the Meter) and meets, at present, every four years. CGPM is responsible for:

- discussing and instigating the arrangements required to ensure the propagation and improvement of the International System of Units;
- confirming the results of new fundamental metrological determinations of the various scientific resolutions of international scope; and
- adopting the important decisions concerning the organization and development of BIPM.

CIPM functions like a board of directors. It consists of eighteen members, each belonging to a different Member Nation. The officers of CIPM issue an Annual Report on the administrative and financial position of the BIPM.

BIPM is the laboratory located just outside of Paris, France. BIPM currently employs about forty physicists and technicians and is responsible for:

- establishing fundamental standards and scales for measurement of the principal physical quantities and maintaining the international prototypes;
- carrying out comparisons of national and international standards;
- ensuring the coordination of corresponding measuring techniques; and

- carrying out and coordinating the determinations relating to the fundamental physical constants that are involved in the above activities.

Because BIPM cannot possibly conduct all research on all aspects of metrology, CIPM has established eight Consultative Committees which are designed to provide CIPM with information on relevant matters for study and advice. These committees coordinate international work and propose recommendations concerning units.

The eight committees are for electricity, photometry and radiometry, thermometry, definition of the meter, definition of the second, ionizing radiation, units, and mass and related quantities.

The United States plays a major role in CGPM, CIPM, BIPM and the Consultative Committees, primarily through NIST.

Other standards organizations including the International Organization for Standardization (ISO), American National Standards Institute (ANSI), Institute of Electrical and Electronics Engineers (IEEE), and the American Society for Testing and Materials (ASTM) establish standards for the practical use of SI units. In a recent move to help insure consistency between standards organizations, IEEE and ASTM are developing a memorandum of understanding that will combine their separate standards documents, ASTM 380 and IEEE 268, into a single document supported by both organizations.

In 1965, the International Organization of Legal Metrology was founded in an attempt to harmonize international legislation involving the use of SI units.

2.3 International System of Units

As science and technology grew, it became necessary for CGPM to add many new units for various kinds of measurements. In 1954, CGPM divided its system of units into base units, supplementary units, and derived units. Finally, in 1960, CGPM named their system of units the **International System of Units,** the symbol for which is SI in all languages. **SI is the modern metric system**. The structure of SI is described in the next section.

3.0 Structure of SI

3.1 Types of SI Units

SI units fall into one of three categories:

- Base Units
- Derived Units
- Supplementary Units

3.2 Base Units

Base units are the fundamental building blocks of SI. The seven base units are as follows:

Unit	Quantity Measured	Symbol
meter	length	m
kilogram	mass	kg
second	time	s
ampere	electric current	A
kelvin	thermodynamic temperature	K
mole	amount of material	mol
candela	luminous intensity	cd

The formal definition of each base unit and the year in which CGPM approved it (shown in parentheses) follow.

meter

The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second. (1983)

Comments:

1. The original definition of the meter was one-ten thousandth of the great circle distance from the north pole to the equator on the meridian that runs through Paris. In 1889 that definition was changed to the distance between two marks on a bar made of a platinum-iridium alloy. This bar was known as the *international prototype meter*. In 1960 the definition of the meter was changed again to 1,650,763.73 wavelengths of the orange-red line of krypton 86.

2. The above changes in definition did not change the length of the meter, but they were made to increase the precision to which the length of the meter can be determined.

3. Today, the meter can be measured with a relative uncertainty of about one or two parts in 10^{10}.

kilogram

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram. (1889)

Comments:

1. The international prototype is made of a platinum-iridium alloy. It is kept at the BIPM under conditions specified by the 1st CGPM in 1889.

2. The original unit of mass in the metric system was the gram. A gram was defined as the mass of a cubic centimeter of water whose temperature was such that the water was at its maximum density (slightly above freezing).

3. The terms mass and weight are often confused. The term *weight* may mean either mass or force. Since force is defined as mass time acceleration, mass and force are two different types of quantities. Thus, the word weight should be avoided, and the correct term, either mass or force, should be used instead.

4. The kilogram is the only base unit that contains a prefix. Names for multiples and submultiples for units of mass are formed from the gram.

5. A mass of one kilogram can be measured to about one part in 10^8.

second

The second is defined as the duration of 9,192,631,770 cycles of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom. (1967)

Comments:

1. The original definition of the second was 1/86,400 of the mean solar day. This definition was not precise enough for current needs.

2. In 1960 the definition of the second based on the mean solar day was changed to a definition based on the tropical year.

3. The second can now be measured to a precision of a few parts in 10^{14}.

ampere

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length. (1948)

Comment:

1. The ampere can be measured to a precision of about one part in 10^7.

kelvin

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. (1967)

Comments:

1. In 1954 the unit of thermodynamic temperature was defined in terms of the triple point of water (point at which water exists in equilibrium as a solid, liquid, and vapor). The triple point of water was assigned the temperature 273.16 K.

2. In 1967, CGPM adopted the name kelvin with the symbol "K", instead of "degree Kelvin" with symbol (˚K) and defined the kelvin as stated in Comment 1.

3. CGPM also decided in 1967 that the kelvin and its symbol K should be used to express an interval or a difference of temperature.

4. In addition to using the kelvin for thermodynamic temperature, use also is made of the degree Celsius. This unit is discussed in more detail later in this manual.

mole

1. The mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

2. When the mole is used, the elementary entities must be specified. These entities may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. (1971)

   Comments:

   1. The mole was not one of the six original base units when the set of base units was adopted in 1954. It was added in 1971.

   2. Note that this definition also specifies the nature of the quantity whose unit is the mole.

candela

The candela is the luminous intensity in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian. (1979)

Comments:

1. The steradian is designated as a supplementary unit, and is defined in Section 3.4.

2. Prior to 1948 units of luminous intensity were based on flame or incandescent filament standards. Because of inaccuracies in these kinds of units, the "new candle" unit, based on the luminance of a blackbody under a pressure of 101.325 kPa at the temperature of freezing platinum (1772 ˚C) was proposed. This unit was adopted in 1948 and the name *candela* replaced the name *new candle*.

3.3 Derived Units

Derived units are formed by algebraic combinations of base units and/or supplementary units. There is only one derived unit for each physical quantity type. Some examples of derived units follow.

Quantity measured	**SI unit**	**Symbol**

area	square meter	m^2
volume	cubic meter	m^3
speed	meters per second	m/s
acceleration	meters per second squared	m/s^2

Nineteen derived units (shown below) have been given special names. Note that these unit names and symbols may be used to express names and symbols for other derived units.

Quantity	Unit Name	Symbol	**Expression in terms of** other units	base units
frequency	hertz	Hz		s^{-1}
force	newton	N		$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$

Quantity	Unit Name	Symbol	**Expression in terms of** other units	base units
electric charge quantity of electricity	coulomb	C	A s	$s \cdot A$
electric potential, potential difference, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature	degree Celsius	˚C	K	
luminous flux	lumen	lm		$cd \cdot sr$
illuminance	lux	lx	lm/m^2	$m^{-2} \cdot cd \cdot sr$
activity (radionuclide)	becquerel	Bq		s^{-1}
absorbed dose, specific energy imparted, kerma, absorbed dose index	gray	Gy	J/kg	$m^2 \cdot s^{-2}$
dose equivalent, dose equivalent index	sievert	Sv	J/kg	$m^2 \cdot s^{-2}$

3.4 Supplementary Units

Supplementary units are dimensionless derived units. There are two supplementary units, the radian and steradian.

Unit	Quantity Measured	Symbol
radian	measures plane angles	rad
steradian	measures solid angles	sr

A formal definition of each unit is given below.

radian A radian is an angle between two radii of a circle that yields an arc length of the circle equal to the length of the radius, as shown in Figure 1.

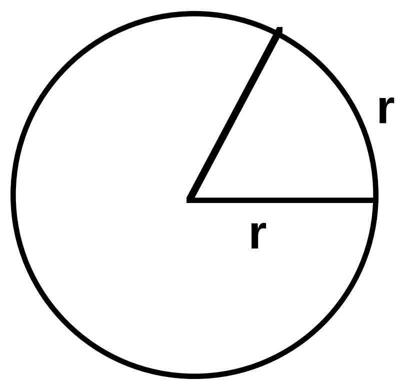

Figure 1: Radian

steradian A solid angle that gives a surface area equal to the square of the radius of the sphere as shown in the following figure.

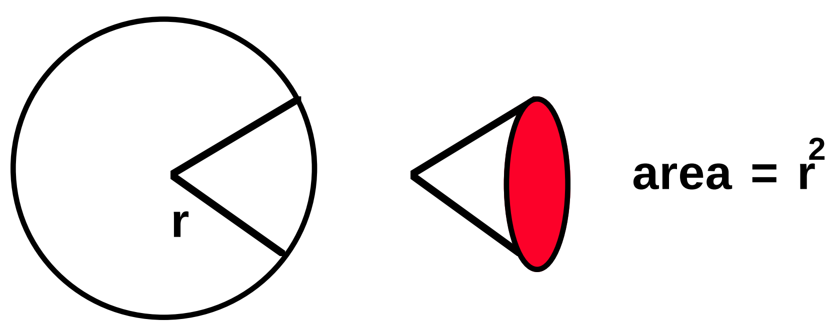

Figure 2: Steradian

3.5 SI is a Coherent System

Because derived units are formed by algebraic combinations of base units and supplementary units without any numerical factor (other than 1), SI is called a *coherent system* of units. Being a coherent system is both good and bad. It is good because a coherent system is both simple and consistent. It is bad because sometimes the derived units are not of a convenient size for many common applications.

4.0 Multiples and Submultiples of SI Units

4.1 Prefixes

A single unit is not practical for all kinds of measurements. For example, the meter is much too large to measure items on a molecular scale, and much to small to measure distances on an interplanetary scale. To accommodate the use of larger and smaller units, SI has provided for decimal multiples and submultiples of SI units. Names for these units are formed by adding prefixes to SI units. The prefix indicates the power of 10 used to construct the unit. The list of SI prefixes, their symbols, and their definitions are shown in the following table.

Prefix	Symbol	Size	
deci	d	0.1	$= 10^{-1}$
centi	c	0.01	$= 10^{-2}$
milli	m	0.001	$= 10^{-3}$
micro	µ	0.000 001	$= 10^{-6}$
nano	n	0.000 000 001	$= 10^{-9}$
pico	p	0.000 000 000 001	$= 10^{-12}$
femto	f	0.000 000 000 000 001	$= 10^{-15}$
atto	a	0.000 000 000 000 000 001	$= 10^{-18}$
zepto	z	0.000 000 000 000 000 000 001	$= 10^{-21}$
yocto	y	0.000 000 000 000 000 000 000 001	$= 10^{-24}$

Multiples

Prefix	Symbol	Size	
deka	da	10	$= 10^{1}$
hecto	h	100	$= 10^{2}$
kilo	k	1000	$= 10^{3}$
mega	M	1,000,000	$= 10^{6}$
giga	G	1,000 000,000	$= 10^{9}$
tera	T	1,000,000,000,000	$= 10^{12}$
peta	P	1,000,000,000,000,000	$= 10^{15}$
exa	E	1,000,000,000,000,000,000	$= 10^{18}$
zetta	Z	1,000,000,000,000,000,000,000	$= 10^{21}$
yotta	Y	1,000,000,000,000,000,000,000,000	$= 10^{24}$

In the United States the spelling *deka* is used for the prefix meaning 10. In many countries this prefix is spelled *deca.*

Symbols for multiples and submultiples of metric units are formed by combining the symbol for the prefix with the symbol for the SI unit as shown in the following examples.

Unit Name	Symbol	Size of unit
milli**m**eter	mm	0.001 m
nano**s**econd	ns	0.000 000 001 s
kilo**j**oule	kJ	1000 J
mega**g**ram	Mg	1,000,000 g (or 1000 kg)

4.2 SI Units

It is important to understand that each physical quantity has only one SI unit, even if the name of this unit can be expressed in different forms. However, the same SI unit can correspond to several different quantities.

An example of the same SI unit used for two different quantities is the joule per kelvin (J/K). This is the unit for both heat capacity and entropy. A second example is the ampere (A) which is the SI base unit for quantity of electric current and also for the derived quantity magnetomotive force. As a consequence, the name of the unit is not always sufficient to define the quantity measured.

A derived unit can often be expressed in several different ways by using names for base units or by using special names of derived units. For example, the unit of energy, the joule, may also be written newton meter or kilogram meter squared per second squared. In practice, preference is usually given to a special unit name or combinations of units in order to differentiate between quantities having the same dimension. For example, the SI unit of energy is the joule while the SI moment of force is the newton meter. Also, the SI unit of frequency is the hertz (Hz), not the reciprocal second.

Standards organizations don't always agree on how to write metric units. For example, ISO says that either a raised dot, or a space may be used as shown in the following example:

N·m or N m

However, ANSI/IEEE in Std 268-1982 states that in the USA, only the raised dot is to be used.

4.3 Non-SI Units

Because they are in common use in many fields, the following non-SI units may be used with SI units:

Name	Symbol	Value in SI units
minute	min	1 min = 60 s

hour	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 86,400 s
degree	°	1 ° = (π/180) rad
minute	'	1 ' = (1/60) ° = (π/10,800) rad
second	"	1 " = (1/60) ' = (π/648,000) rad
liter	l or L	1 L = 1 dm^3 = 10^{-3} m^3
tonne	t	1 t = 10^3 kg

Notes:

1. Either a lowercase or an uppercase l may be used as the symbol for liter. The uppercase l was introduced to avoid confusion with the number 1. In the United States ANSI/IEEE recommend the use of the uppercase L.

2. In some English speaking countries the unit *tonne* is also called the *metric ton*.

There are some units which are not part of the System of International Units, but which are useful in certain fields. Their values are expressed in SI units, but they are obtained experimentally, hence are not known exactly. Here are some example of these types of units:

Name	Symbol	Value in SI units
electron volt	eV	1 eV = 1.602 177 33 (49) x 10^{-19} J
unified atomic mass unit	u	1 u = 1.660 540 2(10) 10^{-27} kg

Notes:

1. The electron volt is the kinetic energy acquired by an electron in passing through a potential difference of 1 volt in a vacuum.

2. The unified atomic mass unit is equal to $^1/_{12}$ of the mass of an atom of the nuclide ^{12}C.

4.4 Non-SI Units that may be used temporarily

There is a collection of non-SI units which are standard in certain fields or certain countries. It is acceptable to use these units on a temporary basis, until CIPM deems their use no longer necessary. These units should not be introduced where they are not used at present.

Name	Symbol	Value in SI units	
nautical mile		1 nautical mile	= 1852 m
knot		1 nautical mile per hour	= (1852/3600) m/s
angstrom	Å	1 Å = 0.1 nm	= 10^{-10} m
are	a	1 a = dam^2	= 100 m^2
hectare	ha	1 ha = 1hm^2	= 1000 m
barn	b	1 b = 100 fm^2	= 10^{-28} m^2

bar	bar	1 bar	= 0.1 MPa	= 100 kPa = 10^5 Pa
gal	Gal	1 gal	= 1 cm/s^2	= 10^{-2} m/s^2
curie	Ci	1 Ci	= $3.7x10^{10}$ Bq	
roentgen	R	1 R	= $2.58x10^{-4}$ C/kg	
rad	rad	1 rad	= 1 cGy	= 10^{-2} Gy
rem	rem	1 rem	= 1cSv	= 10^{-2} Sv

The metric system has taken slightly different forms in the past 200 years. One difference between the systems has been in defining the set of base units. In mechanics, the CGS (centimeter-gram-second) system was used. Some units that were common to this system are not part of SI, and should no longer be used. Units with special names, as shown in the following table, are examples of these types of units.

Name	**Symbol**	**Value in SI units**		
erg	erg	1 erg = 10^{-7} J		
dyne	dyn	1 dyn	= 10^{-5} N	
poise	P	1 P	= 1 dyn·s/cm^2	= 0.1 Pa·s
stokes	St	1 St	= 1 cm^2/s	= 10^{-4} m^2/s
gauss	Gs, G	1 Gs corresponds to 10^{-4} T		
oersted	Oe	1 Oe corresponds to (1000/4π) A/m		
maxwell	Mx	1 Mx corresponds to 10^{-8} Wb		
stilb	sb	1 sb	= 1 cd/cm^2	= 10^4 cd/m^2
phot	ph	1 ph	= 10^4 lx	

Other units which should not be used are:

Name	**Value in SI units**		
fermi	1 fermi	= 1 fm	= 10^{-15} m
metric carat	1 metric carat	= 200 mg	= $2x10^{-4}$ kg
torr	1 torr	= 101,325/760 Pa	
standard atmosphere (atm)	1 atm	= 101 325 Pa	
kilogram-force (kgf)	1 kgf	= 9.806 65 N	
micron (υ)	1 υ	= 1 υm	= 10^{-6} m
stere(st)	1 st	= 1 m^3	

Spelling of meter and liter

The U.S. spelling of unit names meter and liter is a point of contention among many metric advocates in the United States. ISO (and BIPM) use the -re spelling for units meter and liter. That is, BIPM and ISO spell these unit names *metre* and *litre* (along with their multiples and submultiples such as kilometre and millimetre). ISO and BIPM base their spelling on the British Oxford Dictionary.

However, the U.S. Department of Commerce has stipulated that the United States will use the -er spelling. This spelling is consistent with what is found in U.S. dictionaries.

The authority for determining how we should spell these unit names comes from Section 4 of the Metric Conversion Act of 1975 states that....

> *... the metric system of measurement as the International System of Units as established in 1960 by the General Conference on Weights and Measures and interpreted or modified for the United States by the Secretary of Commerce.*

CGPM recognizes both spellings as being correct, and ISO does not specifically state that these unit names should be spelled metre and litre. Other countries that use the -er spelling include Germany, Sweden, Malaysia, and Pakistan.

Using Hyphens

In the U.S. it is common to use a hyphen when the number preceding the unit name is used as an adjective. A common example of this usage is 35-mm film in which case the number 35 is used as an adjective. (This usage is different from describing the film as being 35 mm wide.) For normal usage, SI specifies that there should always be a space between the number and the symbol for the unit.

ISO

The international standard for using SI units is published by the International Organization for Standardization, known as ISO. ISO is an international organization whose members are the national standards bodies of some 90 countries. There is one member standards organization from each country. (In the United States that body is is the American National Standards Institute, or ANSI.) ISO is involved in standards of many different kinds, not just standards of measurement. The document that gives ISO metric standards is known as ISO 1000.

Paper Sizes

In the United States the standard paper size is $8^1/_2$ by 11 inches. There is also an international standard size for paper size known as A4. A4 is slightly longer and slightly narrower than $8^1/_2$ by 11 inches. (A4 is 210 mm by 297 mm or about $8^1/_4$ inches by $11^5/_8$ inches.)

The A-series of paper sizes dates back to an era when paper was made in rectangular forms. A standard size form was 841 mm by 1189 mm. The ratio of the length of the short side to the length of the long side is 1 to $\sqrt{2}$. (Note that the area of this form is about one square meter.) A sheet of paper this size was known as A0.

By cutting a sheet of A0 paper in half (parallel to the short side as shown in Figure 3), the ratio of the short side to the long side of this new size is still 1 to $\sqrt{2}$. The smaller sheets are known as A1. Continuing this approach, sizes A2, A3, A4, etc. can be generated as shown in Figure 3.

A4 is often call *metric paper*, but this is a misnomer. The A-series of paper sizes has been adopted by ISO as an international standard. Paper sizes are not part of the metric system or the System of International Units. However, using A4 paper is simply one more example of the U.S. adopting an international standard which is used in most of the rest of the world.

Most new copiers and laser printers are already equipped to handle A4 paper with just a simple adjustment in a setting. Old file cabinets which are just 11 inches wide may pose a more difficult problem since A4 paper is more than 11 inches long. If the file cabinets are more than 11 inches deep, one solution is to orient the file folders similar to those lateral file cabinets.

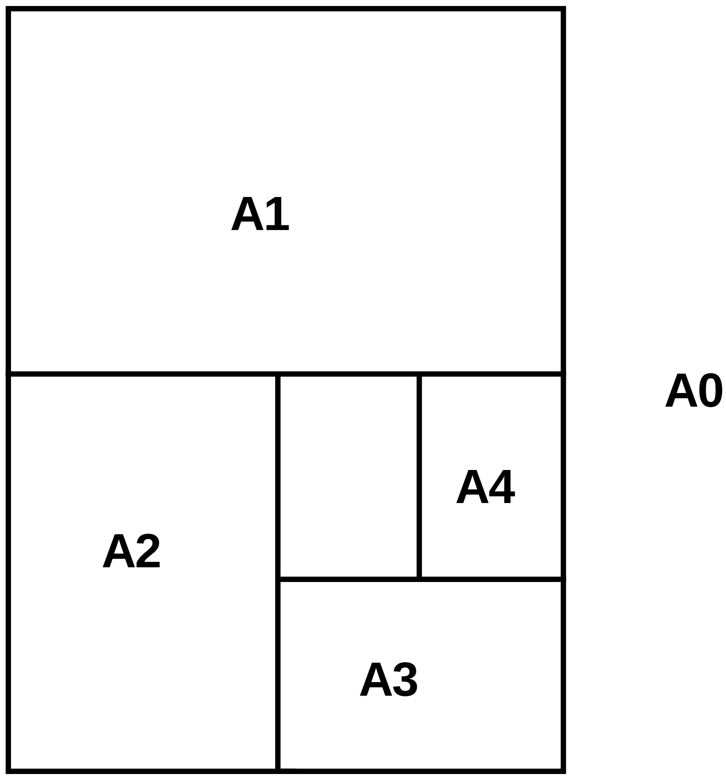

Figure 3: Paper Sizes

There is also an ISO standard B-series of paper sizes intended for specialized use such as posters. B0 is 1000 mm by 1414 mm.

In addition to paper sizes, ISO has also adopted envelope sizes as well.

Using ISO A-series paper sizes has some distinct advantages over the use of $8^1/_2$ x 11.

1. Simplified inventories: All of the A sizes can be cut from one piece of paper if you start with A0. This sequence also eliminates many form sizes as well.

2. Economy in reduction: With a 50% reduction, two pages can be combined into one with no loss of space.

3. Reduction in the number of envelope sizes: ISO has only a small number of envelope sizes, all of which meet all of the international mail requirements. At present there are far more envelope sizes in the U.S.

4. Microfilm proportion: The ratio of 1:√2 is the same ratio as microfilm, so the use of A4 paper increases the efficiency of microfilming. (Although in the digital age the use of microfilm is declining.)

5. Paper weights: The U.S. currently has a variety of ream-based paper weights. In metric countries paper weights are expressed in grams per square meter. Because the A sizes related directly to an area of one square meter, the calculation of paper weights is easy to perform.

6. International Standard: Well over 90% of the rest of the world uses A4 paper. Converting to A4 paper would be one more step in U.S. compliance with international standards.

5.0 Converting between inch-pound and metric units

There are two levels of conversion between inch-pound and metric units. The first level is usually referred to as *exact conversion*. In this type of conversion it is assumed that the given measurement is exact, and converting to the other system simply involves multiplying by the appropriate conversion factor. The following two examples illustrate this type of conversion.

Exact conversion from inch-pound to metric

Example 1: Convert 187 pounds to kilograms.

187 pounds = 187 pounds x 0.4535924 kilogram per pound = 84.8217788 kilograms

Exact conversion from metric to inch-pound

Example 2: Convert 23 square meters to square feet.

23 square meters = 23 square meters x 10.76391 square feet per square meter = 247.56993 square feet

Remark: Exact conversion isn't always exact in the mathematical sense. Many of the conversion factors in Appendix A are rounded to seven significant digits. (Exact conversion factors are indicated with an asterisk.) Therefore, multiplying by the conversion factor introduces some error because the factor has been rounded.

In most practical applications measurements are not exact, and it is necessary to consider precision, accuracy, significant digits, and/or tolerances. These terms are defined as follows.

If m is the true measurement and a is the measured value, then the error in the measurement is given by

$$e = m - a$$

The precision of the measurement is the absolute value of e. The accuracy of the measurement is the relative error in the measurement, which is given by

$$\frac{m - a}{m}$$

The number of significant digits is the number of digits in a number excluding all zeros before the first non-zero digit and possibly excluding the number of zeros after the last non-zero digit. That is, the zeros after the last digit may or may not be significant.

Tolerance: the amount by which a quantity is allowed to vary.

The general rule to follow in converting from one system to another is as follows:

Rule: In all conversions between measurement systems, accuracy should be neither sacrificed nor exaggerated.

ASTM has specificly addressed this issue in their publication *Standard Practice for Use of the International System of Units*, ASTM E380. This publication discusses two methods for relating tolerances and the degree of accuracy required.

Method A: Round endpoints of the limits.

Method B: Convert so that the tolerances in the new system are no larger than the tolerances in the old system.

The differences between the two methods can be illustrated by the following example:

Example 3: Given a measurement of 16.4 inches with a tolerance of 0.1 inch. (Thus, the true measurement must be between 16.3 and 16.5 inches.)

Using Method A we use the following steps:

Step 1: Compute the maximum and minimum allowable dimensions.

$16.4 - 0.1 = 16.3$ and $16.4 + 0.1 = 16.5$

Step 2:: Convert 16.3 and 16.5 inches to millimeters by multiplying by 25.4.

$16.3 \times 25.4 = 414.02$

$16.5 \times 25.4 = 419.10$

Step 3: Round to the appropriate number of decimal places according to the following table.

Original tolerances in inches

at least	less than	Round to nearest (in millimeters)
0.000 04	0.000 4	0.0001
0.000 4	0.004	0.001
0.004	0.04	0.01
0.04	0.4	0.1
0.4		1

Thus, the new limits would be 414.0 mm and 419.1 mm since rounding should occur to the nearest 0.1 millimeter.

Using Method B, the first two steps are the same, however the lower limit would be 414.1 because 414.0 is outside of the original tolerance.

6.0 Rules for using SI units and unit symbols

1. When SI unit names are written in full, the unit names do not begin with a capital letter except at the beginning of a sentence or in the case where other words are also capitalized, such as in titles. The only exception is the unit, degree Celsius. The word *degree* is not capitalized, however the modifier, *Celsius*, is capitalized.

2. Unit symbols are written with lowercase letters except for the following cases:

    a. The first letter is uppercase when the name of the unit is drived from the name of a person. (Example: pascal has the symbol Pa.)

    b. The recommended symbol for liter is L, although both l or L are recognized as being acceptable.

3. Symbols for prefixes which are multiples and larger than 1000 (mega, giga, tera, peta, exa, zetta, yotta) are written with uppercase letters. All other symbols for prefixes are lowercase. (Examples: Mg is the symbol for megagram, mg is the symbol for milligram.)

4. When prefix names are written out, lowercase letters are used except where the entire unit name is written in uppercase letters or where the written-out prefix is the first word in a sentence.

5. When unit names are written out in full, write the prefix in full also. (Example: the correct form is megahertz, not mHertz or megaHz.)

6. When written out in full, unit names are made plural when required by the rules of English grammar. (Example: one meter, ten meters.) Fractions, both common and decimal, are always treated as singular. (Example: $^1/_2$ meter, 0.5 meter, not 0.5 meters.) The unit names hertz, lux, and siemens are the same in the singular and plural.

7. A period is not used after a symbol unless the symbol occurs at the end of a sentence.

8. The dot (period) is used as the decimal marker and is placed on the line[2]. In numbers less than one, a zero must be written to the left of the decimal point (0.5, not .5)

9. When joining a prefix and an SI unit symbol together, do not leave a space between the prefix and the unit symbol (kPa not k Pa).

10. Do not use a unit symbol unless it is preceeded by a number. (Write out the entire unit name if there is no number preceeding it.)

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[2] In some countries a comma is used as a decimal marker. In these countries, spaces are used instead of commas. Thus, the number 186,000 would be written 186 000 to avoid confusion.

11. When a symbol follows a number (to which the symbol refers), leave a space between the number and the symbol (400 m, not 400m). The only exception is made when using degree, minute, and second to express plane angles[3]. This exception is made to accommodate some industry standards which do not leave a space for these angular measurements. CIPM and ISO recommend using a space even in these cases. Note that in the symbol °C there is no space between ° and C, but there is a space between the number and the symbol (37 °C, not 37°C).

12. Division in an SI symbol is shown with a solidus (slash). Use at most one solidus in a symbol unless parentheses are used. (Example: m/s^2 or (m/s)/s, not m/s/s.)

13. For a compound unit which is the product of two or more units, the symbol is formed by leaving a space between the symbols for each factor, or by using a centered dot to indicate multiplication. (Example: n m or n·m for newton meter.)

14. When spelling out the name of a compound unit, a space is recommended. (Example: newton meter.) A hyphen is acceptable (newton-meter), but never use a raised dot (newton·meter).

15. Do not mix unit names and unit symbols. (Example: m/s and meter per second are acceptable, meter/second and m per s are not.)

16. Unit symbols should be written in upright type, not italics, regardless of the nature of the surrounding text.

17. In tables, SI and customary (inch-pound) units may be shown in parallel columns. If coordinate markings are given in non-SI units on a graph, they should be given secondary status (placed along the top instead of the bottom or on the right side of the graph instead of the left. Non-SI units may also be given in smaller-sized text.)

18. Essential data express or interpret quantitative results. All such data should be in SI units. In cases in which the sole use of SI units would compromise good communications or units other than SI units have been specified as a contractural requirement, then quantities should be expressed in SI units followed in parentheses by the same quantities expressed in non-SI units. Some exceptions may be necessary for commercial devices, technical standards, or quantities having special legal significance.

Rules for drafting

The following simple rules should be followed for drawings using metric units.

1. Metric drawings should be labeled *Metric*.

2. Dual units should not be used.

3. Metric scale drawings should be given in ratios. The following table shows suggested ratios for standard inch-pound sacle drawings.

Inch-pound Scale Metric Scale

[3]These are inch-pound units and not SI units, therefore not subject to SI rules. However, their use currently is permitted with SI units as noted in Section 4.3

1" = 1'	1:10
$^{3}/_{4}$ = 1'	1:20
$^{1}/_{2}$ = 1'	1:50
$^{3}/_{8}$ = 1'	1:50
1" = 2'	1:20
1" = 5'	1:50
1" = 10'	1:100
1" = 20'	1:200
1" = 40'	1:500
1" = 50'	1:500 or 1:1000
1" = 200'	1:2000
1" = 400'	1:5000

4. Sheet sizes for drawings will remain the same, at least for the the present.

5. Angular measurements should retain the degree-minute-second convention.

7.0 References

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